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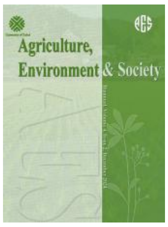

A comparative emergy analysis of rice and cotton farming ecosystems: implications for sustainability

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ABSTRACT

Environmental degradation stemming from excessive consumption of natural resources and chemical inputs threatens resource efficiency and the long-term sustainability of agricultural ecosystems. This study employed a comprehensive questionnaire survey combined with emergy evaluation to assess and compare the efficiency and sustainability of rice and cotton farming ecosystems in Golestan province, Iran, during the 2018–2019 growing season. Results indicated that the total emergy input for rice cultivation (1.01E+17 sej ha^{-1}) substantially exceeded that of cotton (5.14E+16 sej ha^{-1}), highlighting a greater concentration of embodied energy in rice production. In both systems, non-renewable environmental inputs dominated over renewable environmental, purchased renewable, and purchased non-renewable flows. Groundwater emerged as a critical input due to high crop water demand during summer cultivation and negligible seasonal rainfall in the region. The emergy analyses revealed that cotton was more productive per unit emergy invested. Both ecosystems exhibited low emergy renewability, reflecting heavy dependence on non-renewable resources. Cotton demonstrated superior resource efficiency, as evidenced by a higher emergy yield ratio. Economic indicators, including standard and modified emergy investment ratios, showed that rice production incurred significantly higher economic costs and lower efficiency. Environmental loading ratios further indicated that cotton imposed markedly lower environmental pressure, confirming its greater environmental sustainability. Overall, cotton outperformed rice across multiple metrics: production efficiency, resource consumption efficiency, economic efficiency, and environmental sustainability. To enhance the sustainability of such agroecosystems, we recommend reducing reliance on non-renewable purchased inputs and advancing farmer awareness, education, and engagement in sustainable practices.

Highlights

- Rice emergy input (1.01E+17 sej ha^{-1}) exceeds cotton (5.14E+16 sej ha^{-1}) in Golestan, Iran.
- Cotton farming shows higher productivity and efficiency than rice via emergy indices.
- Non-renewable inputs dominate both rice and cotton, with groundwater as top contributor.
- Cotton has lower environmental load (ELR=64) than rice (ELR= 123.13), more sustainable.
- Reducing non-renewable inputs can boost sustainability in rice and cotton ecosystems.

1. Introduction

In recent decades, there has been a rise in the demand for food production, which has led to the expansion of industrial agriculture with its high input consumption and a decline in agricultural sustainability (Gheicari et al., 2021; Lombardi et al., 2021). As a food production system,

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agriculture has accelerated environmental destruction, resource depletion, and global pollution (Montoya et al., 2020). Therefore, food production policies should prioritize addressing pollution and depleted natural resources, in addition to ensuring the sustainability of food production-consumption systems. Beyond resource conservation and healthy production, the utility of agriculture must be considered to ensure the viability of sustainable crop production systems (Lombardi et al., 2021).

Agriculture and energy are intrinsically linked. Agriculture is a consumer of energy on the one hand and a provider of biological energy on the other (Elsoragaby et al., 2019). In the current state of agriculture, product usefulness and productivity depend on the sector's energy efficiency (Kaur et al., 2021). Energy consumption in the agricultural sector has increased more rapidly than in other global economic sectors due to increased mechanization and the use of commercial energy. However, increasing input consumptions for maximum performance can lead to decreased sustainability as environmental resources diminish and environmental pollution rises. Due to the reduction of negative environmental effects, such as the reduction of sustainability, it is necessary to improve energy consumption efficiency. Sustainable agriculture can be achieved through the agricultural sector´s efficient use of resources and energy, which reduces input consumption, the ecological footprint, the emission of greenhouse gases, and the depletion of natural resources (Mousavi avval et al., 2011). Agricultural operations are sustainable when they preserve environmental quality and have social acceptability and economic benefits (Kumaraswamy, 2012). To achieve this, evaluation methods that provide information about the state and rate of change of an ecosystem are required. These methods must consider environmental, social, and economic factors (Quintero-Angel and Gonzales Acevedo, 2018). Methods such as environmental input-output analysis, ecological footprint determination, ecological valuation, life cycle assessment, energy analysis and emergy are used to evaluate a system´s use of resources, pollution, and sustainability (Patterson et al., 2017; Fallahinejad and Armin, 2022).

The advantage of the emergy evaluation method over other methods is that it reflects the various energy and matter flows in the studied system in a single form, indicating both the quantity and quality of these flows (Brown et al., 2016). Emergy analysis examines the viability of an ecosystem comprehensively by converting all flows, natural reserves, and economic resources into solar emergy units (Odum, 1996). By determining the level of sustainability of continuous ecological and economic systems, emergy assessment improves our understanding of these systems and their interrelationships. Emergy indices are a useful tool for integrating ecological-economic systems because they permit the measurement and comparison of different aspects of these ecosystems (Patterson et al., 2017; Shahhoseini and Kazemi, 2022). These indicators can determine the efficacy, renewability, environmental impact, and environmental and economic sustainability of a system (Odum, 2000; Brown and Ulgiati, 2004). Emergy is the total energy consumed by a system, while solar emergy is the amount of available solar energy consumed directly or indirectly to provide a service or produce a good. Emergy is measured in solar emjoules (sej) and is also known as embodied energy and energy memory (Odum, 1996).

Emergy evaluation is used to assess the viability of production systems at various scales (Zhai et al., 2017). The evaluation and comparison of emergy in the two common production systems of fodder corn and wheat in Denmark revealed that the input consumption efficiency and, consequently, the sustainability of the fodder corn production system was greater than that of the wheat system (Ghaley et al., 2018). The evaluation of product production sustainability in India and Pakistan based on emergy analysis revealed that irrigation water and labor inputs comprised the largest proportion of total emergy input in both countries, and the sustainability of agricultural activities in both countries was poor (Ali et al., 2019).

In addition, emergy analysis evaluation of the sustainability of mechanized, conventional, protection, and natural habitat shallot production systems in Iran revealed that natural habitat garlic production was more sustainable than other shallot production systems (Amiri et al., 2021). Using the production function based on emergy, a comparison of traditional and mechanized rapeseed production systems in Iran revealed that the mechanized system was less sustainable than the traditional system (Amiri et al., 2020). Despite theses studies, little research has been conducted on emergy evaluation of agricultural plants on a case-by-case basis.

Rice and cotton are two important agricultural products worldwide. Rice is the primary source of nutrition for over half the world's population, as it dominates the global food market. More than 1.6 million square kilometers of land are used for rice cultivation throughout the world (Zhou et al., 2023).

Iran devoted 596,000 ha to rice cultivation in 2015 and produced 2,900,000 tons of paddy. In the same year, 10% of this crop's Iranian cultivated area was in the Golestan province (Ministry of Agricultural Jihad, 2016). Also, cotton is the most important fiber plant in the world. In addition, cottonseed is a valuable oil- and animal-feeding oilseed. Due to its high value in international trade, cotton is an indispensable component of the agricultural sector. In 2015, cotton was cultivated on 72,000 ha in Iran, and 175,000 tons were harvested. In the same year, 13.39% of the cultivated area for this crop in Iran was in the Golestan province (Kazemi et al., 2018). This study aimed to evaluate and compare the efficiency and sustainability of rice (*Oryza sativa* L.) and cotton (*Gossypium hirsutum* L.) farming ecosystems in Iran, providing recommendations for their optimal and sustainable management.

2. Materials and Methods

2.1. Study area

This research was conducted in Golestan province, Iran, during the 2018-2019 growing season (Figure 1). Located in northern Iran, southeast of the Caspian Sea, Golestan province spans from 36º30' to 38º15' N latitude and 53º51' to 56º14' E longitude. It borders Turkmenistan to the north, Semnan to the south, North Khorasan to the east and Mazandaran to the west. This province´s climate is influenced by the Alborz mountain range, the Caspian Sea, the southern Turkmenistan desert, and forests. According to Demarton's climate classification system, Golestan province has five distinct climates: Mediterranean in the center, dry-desert in the north, semi-arid in the coastal, central, and northeastern parts, humid in the south, and semi-humid in the south (Shahhoseini et al., 2022b).

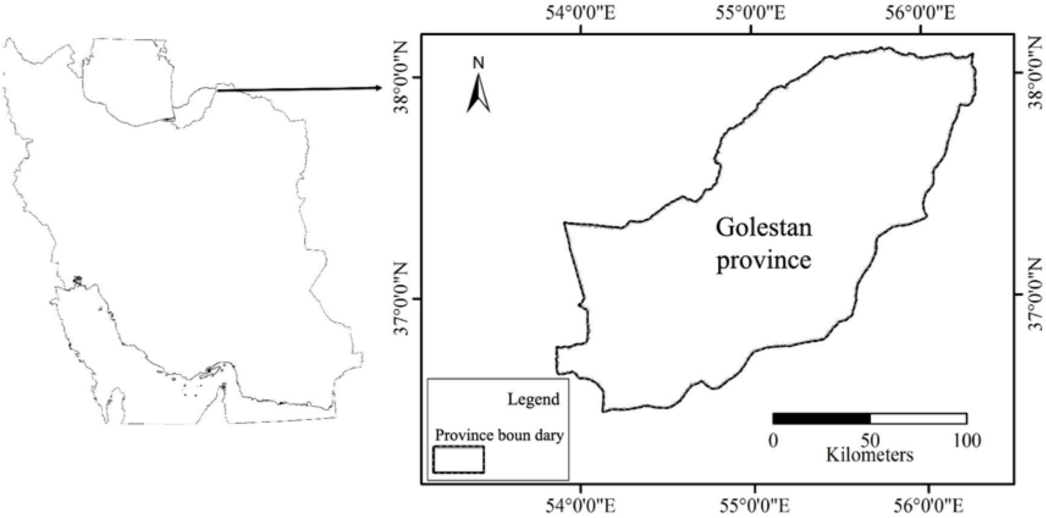

Figure 1. Location of the Golestan province in Iran

2.2. Data collection

Data were collected through questionnaires and face-to-face interviews with farmers. The sample size was calculated using Cochran's method (Eq. 1) (Cochran, 2003).

$$n = \frac{\frac{z^2pq}{d^2}}{1 + \frac{1}{N}\left(\frac{z^2pq}{d^2} - 1\right)} \tag{1}$$

where, n is the sample size, N is the size of the statistical population, z is the standard error of the confidence coefficient (1.96), p is the proportion of the population with a particular trait (0.5), q is the proportion of the population without a specific trait (0.5), and d is the desired accuracy. Farmers were selected by random sampling method.

2.3. Emergy analysis

The first step in emergy analysis is to identify the spatial and temporal boundaries, the most significant system inputs, and the material, energy and economic flows within the system (Figure 2) (Odum, 1996; Odum, 2000). This method categorizes system inputs as environmental or non-environmental, purchased or free, and renewable or non-renewable (Odum, 2000).

Emergy analysis based on dividing all inputs into four groups: renewable environmental inputs (R) such as sunlight, wind, rain and its evapotranspiration; environmental inputs that are potentially renewable, but due to time in their renewal, they are considered non-renewable environmental inputs (N0) such as soil erosion, loss of soil organic matter, groundwater and its evapotranspiration; renewable (F_R) and non-renewable purchased inputs (F_N) (Campbell and Laherrere, 1998; Asgharipour et al., 2019). All the selected farms have been monitored from land preparation to harvest, recording information such as agricultural history of the farm, land preparation operations, planting, fertilizing, spraying, harvesting, consumable inputs such as chemical fertilizers and pesticides, machinery usage, fuel consumtion, labor, and yield. Data on soil erosion, organic matter, and climatic conditions were collected from the Department of Natural Resources and Watershed Management and the Department of Meteorology of Golestan province, respectively (Appendix A).

In this study, the flow of renewable resources was considered identical for both rice and cotton fields. To determine the amount of fertilizers and chemicals, the effective composition of these substances was calculated. The renewability coefficient for each input was also determined. This coefficient is 0.10 for labor, 0.02 for electricity, 0.37 for cotton seed, and 0.43 for rice seedlings (Asgharipour et al., 2020). To calculate the solar emergy of inputs and outputs in rice and cotton agricultural ecosystems, the most significant inputs and were determined per hectare in terms of mass unit (gr) energy unit (J), and monetary unit (Iranian Rial). Details of calculation are shown in Appendix A. The emergy equivalent of rice and cotton yields was estimated to be 1.53E+04 and 1.18E+04 sej g^{-1}, respectively (Erdal et al., 2007). The EXCEL 2019 software was utilized for all emergy analysis calculations.

The amount of solar emergy was calculated by multiplying each input´s numerical value by its respective transformity (Odum, 2000). Emergy evaluation in this study was based on the planetary coefficient of 12.00E+24 seJ yr^{-1}, and the transformities were also determined using this value (Brown at al., 2016). Each farm´s total emergy input was calculated by adding the emergy values of all its inputs. Then, emergy input and emergy output were computed for each of the rice and cotton farming ecosystems by averaging the data from all of the investigated fields. To evaluate sustainability, the indices of transformity (Tr), specific emergy (SpE), emergy yield ratio (EYR), standard emergy investment ratio (EIR), and modified emergy investment ratio (EIR*) emergy renewability (%R), emergy self-support ratio (ESR), standard environmental loading ratio (ELR), modified environmental loading ratio (ELR*), standard emergy sustainability index (ESI), modified emergy sustainability index (ESI*), emergy exchange ratio (EER) and emergy index for sustainable development (EISD) were calculated to evaluate sustainability in rice and cotton farming ecosystems.

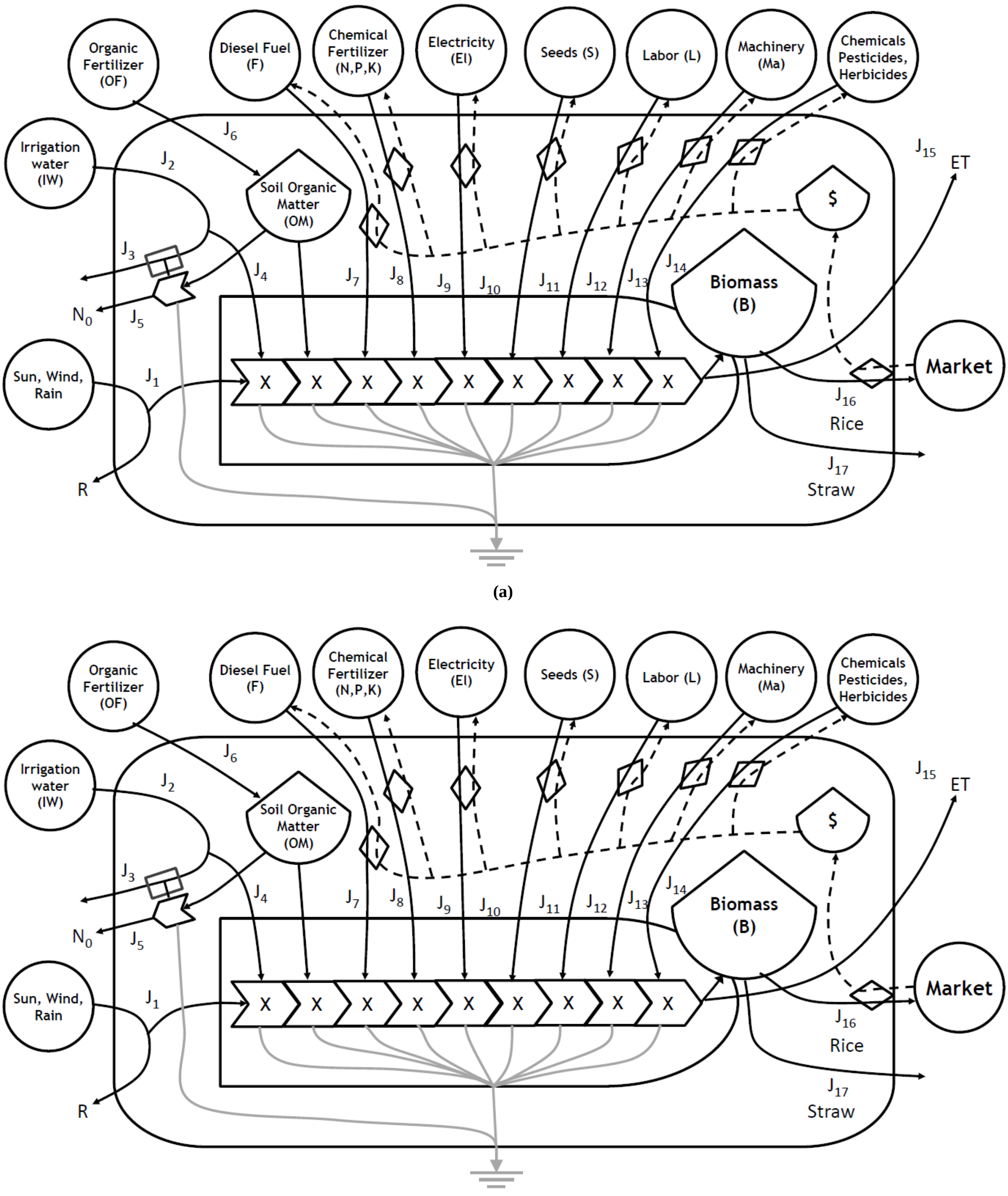

Figure 2. Emergy flow diagram of rice (a) and cotton (b) farming ecosystems in Golestan Province

3. Results and discussion

3.1. The structure of input emergy

Tables 2 and 3 depict the emergy values of the most important flows of environmental resources and purchased inputs, as well as their contributions to the total emergy input in rice and cotton farming ecosystems. The total emergy input, which supports rice and cotton farming ecosystems, is calculated to be 1.01E+17 sej ha^{-1} yr^{-1} (Table 2) and 5.14E+16 sej ha^{-1} yr^{-1} (Table 3). This indicates that the density of emergy in the rice production system is considerably higher than in the cotton production system. This value was reported to be 1.71E+16 sej ha^{-1} ya^{-1} for the potato production system in Iran´s Golestan province (Shahhoseini et al., 2022a).

3.1.1. Renewable environmental inputs (R)

These inputs comprise radiant energy from the sun, kinetic energy from the wind, and chemical energy from precipitation and evaporation. The proportion of these inputs to the total emergy input in rice and cotton farming ecosystems was 0.80% and 1.53%, respectively (Figure 2), indicating a low consumption of renewable natural resources in the production of these two products.

Evapotranspiration of precipitation constitutes the largest portion of renewable environmental inputs in both rice and cotton agricultural systems (Tables 2 and 3). Renewable environmental inputs are directly derived from sunlight energy. Therefore, in order to avoid double counting, the sum of the renewable environmental input with the highest emergy value and sunlight input emergy is considered the total renewable environmental emergy (Amiri et al., 2021). In this study, this was evapotranspiration of rain for both rice and cotton production systems. The greater importance of evapotranspiration of rain compared to other renewable environmental inputs in rice and cotton systems is due to their summer cultivation and the intense sunlight and heat, leading to high evapotranspiration and low rainfall during this season in the study area. In a study evaluating the sustainability of potato farming ecosystems in Golestan province, Iran it was found that rain had the greatest amount of emergy among renewable environmental inputs (Shahhoseini et al., 2022a).

3.1.2. Non-renewable purchased inputs (N_0)

Environmental non-renewable inputs comprised the largest proportion of total emergy input in both rice and cotton farming ecosystems (80.10% and 83.27% for rice and cotton, respectively) (Figure 2). The extremely high proportion of this input in both agricultural ecosystems suggests that the environmental costs of rice and cotton production in the province of Golestan are substantial. Groundwater was the largest nonrenewable environmental input in both rice and cotton production systems. Also, among the 21 inputs analyzed in this study, the proportion of groundwater to total emergy input was the highest in both rice and cotton production systems (Tables 2 and 3). This is primarily due to the high water requirements of rice and cotton, as well as their cultivation during the summer season and the increased need for irrigation due to high evapotranspiration and low rainfall in this season in the study area. In spite of this, the proportion of groundwater input to total emergy input in the rice cropping system was 8% greater than in the cotton cropping system, which is the primary reason for the permanent presence of water beneath rice plants during the crop growing season. Utilizing new rice varieties with a shorter growth period and lower water requirement can effectively reduce water usage. Soil erosion had the second share of the non-renewable environmental inputs in both agricultural systems (25.04 and 28.01% for rice and cotton crops, respectively). Implementing protective tillage methods and using multipurpose machines to reduce the frequency of field entry, as well as using organic fertilizers to prevent erosion and loss of soil organic matter, can effectively reduce the input of emergy to farms. In a similar study on common fodder corn cultivation in Denmark, the share of soil erosion from the total emergy input was 3.3% (Ghaley et al., 2018).

3.1.3. Renewable and non-renewable purchased inputs (F_R, F_N)

Renewable purchased inputs comprised the smallest proportion of environmental and purchased renewable and non-renewable inputs in both rice and cotton cropping systems (2.86 and 1.72%, respectively); Conversely, the share of non-renewable purchased inputs was much higher (16.24 and 13.48 %, respectively, in rice and cotton farming systems) (Figure 2). This demonstrates the high dependence of purchased inputs on non-renewable resources due to the environmental pressure associated with the production of rice and cotton in the study area. In both production systems, the proportion of total purchased inputs to total emergy input was considerably lower than that for free environmental inputs (19.10 and 15.20%, for rice and cotton farming systems, respectively). This suggests that the impact of purchased inputs on rice and cotton production in the study area is minimal. Nonetheless, the contribution of certain purchased inputs to this study was substantial (Tables 2 and 3). Consequently, managing and optimally consuming these purchased inputs, particularly non-renewable inputs, is essential to control and reduce the proportion of non-renewable resources used in product production. In a study, the amount of purchased emergy input for China´s potato ecosystem was calculated to be 9.60E+15 sej ha^{-1} yr^{-1} (Zhai et al., 2017).

The proportion of labor input to total emergy input in cotton production was more than twice that of rice production (5.87 vs 2.59% in cotton and rice farming ecosystems, respectively). This is typically due to manual harvesting in the majority of cotton farms in the study area. Modern cotton harvesting machines can effectively reduce this input while simultaneously improving product quality. In the Iranan city of Khorramabad, the emergy value of the labor force for subsistence and commercial systems of rapeseed production was calculated to be 9.75E+14 and

5.06E+14 sej ha^{-1} yr^{-}, respectively (Amiri et al., 2019). In this study, the proportion of seedling input to total emergy input in rice production was 6%, the highest proportion among all purchased inputs to this system (Table 2). The proportion of seed input to total emergy input in cotton farming was 2.76% (Table 3).

Table 1. Specifications and formula of emergy-based indices for evaluation of race and cotton farming ecosystems

Index	Formula	Specifications	Reference
Renewable environmental inputs	R	Renewable flows from free local resources	(Asgharipour et al., 2019)
Non-renewable environmental inputs	N0	Local potentially renewable flows from free local resources that is being used in a nonrenewable	(Campbell and laherrere, 1998)
Renewable purchased inputs	F_R	Renewable flows from purchased resources	(Asgharipour et al., 2019)
Non-renewable purchased inputs	F_N	Non-renewable flows from purchased resources	(Asgharipour et al., 2019)
Total emergy input	$U=R+N0+F_R+F_N$	Total emergy resources required to support the production system	(Asgharipour et al., 2019)
Total emergy output	$Y= R+N0+F_R+F_N$	Total emergy of system products	(Asgharipour et al., 2019)
Market value of the economic yield (Rials g^{-1})	Y_M	Money received for the crops when sold	(Asgharipour et al., 2020)
Transformity	$\mathrm{Tr} = \frac{\mathrm{U}}{\mathrm{AE}}$	Amount of emergy required to produce an output unit in joules. AE is the accessible energy of the product	(Brown and Ulgiati, 2004)
Specific emergy	$\mathrm{SpE} = \frac{\mathrm{U}}{\mathrm{W}}$	Amount of emergy required to produce an output unit in grames. W is the mass of the product	(Brown and Ulgiati, 2004)
Emergy renewability	$\%\mathrm{R} = \frac{\mathrm{R + FR}}{\mathrm{U}} \times 100$	Percentage of the renewable energy used by the system	(Odum, 2000)
Emergy yield ratio	$\mathrm{EYR} = \frac{\mathrm{Y}}{\mathrm{FR + FN}}$	Ability of a process to use renewable and nonrenewable environmental resources with economic resources as a capital	(Odum, 2000)
Standard emergy investment ratio	$\mathrm{EIR} = \frac{\mathrm{FR + FN}}{\mathrm{R + N0}}$	Indicates the intensity of economic investment and its matching to the free renewable and nonrenewable resources of the environment	(Asgharipour et al., 2019)
Modified emergy investment ratio	$\mathrm{EIR}^* = \frac{\mathrm{FR + FN}}{\mathrm{R}}$	The ratio of purchased resources to renewable environmental resources, alone	(Asgharipour et al., 2020)
Emergy self-support ratio	$\mathrm{ESR} = \frac{\mathrm{R + N0}}{\mathrm{U}}$	Measure of production system dependence on the environment	(Zhai et al., 2017)
Standard environmental loading ratio	$\mathrm{ELR} = \frac{\mathrm{N0 + FR + FN}}{\mathrm{R}}$	Environmental pressure produced by a process	(Lu et al., 2014)
Modified environmental loading ratio	$\mathrm{ELR}^* = \frac{\mathrm{N0 + FN}}{\mathrm{R + FR}}$	Environmental pressure produced by a process	(Lu et al., 2014)
Standard emergy sustainability index	$\mathrm{ESI} = \frac{\mathrm{EYR}}{\mathrm{ELR}}$	Measure of the sustainability of the system	(Lu et al., 2014)
Modified emergy sustainability index	$\mathrm{ESI}^* = \frac{\mathrm{EYR}}{\mathrm{ELR}^*}$	Measure of the sustainability of the system	(Lu et al., 2014)
Emergy exchange ratio	$\mathrm{EER} = \frac{\mathrm{YM}}{\mathrm{U}}$	Emergy exchange ratio based on crop yield per unit area	(Asgharipour et al., 2020)
Emergy index for sustainable development	$\mathrm{EISD} = \frac{(\mathrm{EYR} \times \mathrm{EER})}{\mathrm{ELR}}$	This index evaluates the effects of market feedback on the system´s environmental sustainability and the effects of market exchange on the emergy performance of the system	(Asgharipour., 2020)

According to questionnaire results, rice transplanting and cotton seeding were performed manually and in excess of the recommended amounts on most farms. Training farmers on proper planting methods and, as much as possible, useing planting machines can effectively reduce the consumption of these inputs, thereby reducing emergy inputs and increasing the crop production system´s efficiency. Encouraging and financially supporting farmers, such as providing low-interest loans for the purchase of suitable planting machines, is crucial in this regard. For the production of rice (Table 2) and cotton (Table 3), nitrogen fertilizer represented the second (5.63%) and third (2.52%) largest portion of the total emergy input. In addition, phosphorus fertilizer contributed significantly (2.79%) to the total emergy input among the many purchased inputs in the rice farming system. The use of organic fertilizers to the greatest extent possible can effectively reduce the proportion of chemical fertilizers, thereby reducing the consumption of nonrenewable resources and improving the product health.

3.2. Emergy-based indicators

Emergy indices are used to measure the productivity, renewability, environmental impact, and sustainability of production systems (Odum, 2000; Brown and Ulgiati, 2004). The evaluation of these indicators in ecosystems has assisted in identifying and quantifying their environmental and economic effects and sustainability, and its results are applicable at both the local and global levels for farmers and policymakers to make the best decision to achieve sustainable agriculture (Asgharipour et al., 2019).

Table 2. Natural and economic flow, renewability, transformity and solar emergy for rice

Variable	Unit	Raw annual flow	Renewability factor	Solar transformity (sej unit^{-1})	Solar emergy (sej ha^{-1} yr^{-1})	Solar emergy (%)	References for transformity
Renewable environmental inputs							
Solar energy	J	2.99E+13	1	1.00E+00	2.99E+13	0.02	definition
Wind, kinetic energy	J	1.05E+10	1	1.25E+03	1.31E+13	0.01	(Campbell and Erban, 2017)
ˡRain, chemical	J	2.60E+10	1	2.25E+04	5.85E+14	0.56	(Asgharipour et al., 2019)
Rain evapotranspiration	J	2.18E+10	1	2.88E+04	7.87E+14	0.77	(Asgharipour et al., 2019)
Subtotal					8.17E+14	0.80	
Non-renewable environmental inputs							
Groundwater	J	2.26E+11	0	1.92E+05	4.34E+16	42.97	(Cuadra and Rydberg, 2006)
Groundwater evapotranspiration	J	8.53E+10	0	2.88E+04	2.46E+15	2.43	(Asgharipour et al., 2019)
SoilOrganicMatterreduction	J	9.49E+10	0	9.36E+04	8.88E+15	8.79	(Brandt-Wiliams, 2002)
Soil erosion	J	2.06E+07	0	1.27E+09	2.62E+16	25.04	(Odum, 1996)
Subtotal					8.09E+16	80.10	
Purchased inputs							
Nitrogen fertilizer	g	1.85E+05	0	3.09E+10	5.69E+15	5.63	(Brandt-Wiliams, 2002)
Phosphorus fertilizer	g	1.00E+05	0	2.82E+10	2.82E+15	2.79	(Brandt-Wiliams, 2002)
Potash fertilizer	g	1.00E+05	0	2.23E+09	2.23E+14	0.22	(Odum, 1996)
Micro fertilizer	g	3.00E+03	0	3.91E+09	1.17E+13	0.01	(Lan et al., 2002)
Herbicide	g	3.50E+03	0	1.89E+10	6.62E+13	0.06	(Hu et al., 2010)
Insecticide	g	9.00E+03	0	1.89E+10	1.70E+14	0.16	(Hu et al., 2010)
Machinery	g	1.34E+04	0	1.01E+10	1.35E+14	0.13	(Campbell et al., 2005)
Fossil fuel and lubricant	J	1.19E+10	0	8.60E+04	1.02E+15	1.00	(Odum, 1996)
Electricity	J	3.60E+09	0.02	2.31E+05	8.32E+14	0.82	(Asgharipour et al., 2019)
Human labor	J	1.18E+09	0.10	2.22E+06	2.62E+15	2.59	(Lu et al, 2009)
Installation of irrigation	Rials	0.00E+00	0	2.50E+08	0.00E+00	0.00	(Amiri et al., 2020)
Seed	Rials	0.00E+00	0.37	6.76E+07	0.00E+00	0.00	(Lan et al., 2002)
Transplant	Rials	6.08E+15	0.43	1.00E+00	6.08E+15	6.00	definition
Subtotal					1.97E+16	19.10	
Total					1.01E+17	100.00	
Economic yield	g	675E+06		1.50E+10	1.01E+17		Calculated
Economic yield	J	1.03E+11		9.81E+05	1.01E+17		Calculated

3.2.1.Transformity (Tr) and Specific emergy (SpE)

The average economic yield in rice and cotton farming ecosystems was 6750 and 4500 kg ha^{-1}, respectively, which shows the efficiency of these two production systems in converting inputs into economic outputs. In addition, the emergy allocated to economic performance in rice and cotton production systems in Golestan province was estimated to be 1.07E+17 and 5.14E+16 sej ha^{-1} yr^{-1}, respectively. As unit emergy values, Tr and SpE indicate the effectiveness of a production system. Lower values of these indicators suggest greater performance and efficiency in environmental and economic competition; this translates to less emergy input per unit of output product (Odum, 2000). The magnitudes of Tr and SpE in the rice farming ecosystem were 9.81E+05 sej J^{-1} and 1.50E+10 sej g^{-1}, whereas in the cotton farming ecosystem, these values were 9.68E+05 sej J^{-1} and 1.14E+10 sej g^{-1}, indicating that the cotton farming ecosystem in Golestan province has higher production efficiency than the rice farming ecosystem.

In this study the Tr of rice and cotton production was greater than the values of 8.02E+05 and 2.60E+05 sej J^{-1} for subsistence and commercial rapeseed production systems in Iran, respectively (Amiri et al., 2019). In this study, the amount of SpE for the production of rice and cotton was less than 2.25E+10 sej g^{-1} and greater than 7.24E+09 sej g^{-1}, respectively, compared to subsistence and commercial rapeseed production in Iran (Amiri et al., 2019).

3.2.2. Emergy renewability (%R)

This index indicates the proportion of renewable resources used to support a production system (Odum, 2000). In this study, the %R of both cropping systems was low (3.67 and 3.17% for rice and cotton cropping systems, respectively) (Table 4). In other words, 96.33 and 96.83% of the total emergy input in rice and cotton production systems, respectively, depended on non-renewable resources, primarily related to groundwater, soil erosion and loss of soil organic matter. It is possible to increase the agricultural system´s renewability and thus its sustainability by minimizing the proportion of these resources in rice and cotton farming ecosystems. As non-renewable resources become scarcer over time, increasing the proportion of renewable resources and decreasing the consumption of non-renewable resources in a production system increases that system´s economic competitiveness and, consequently, its long-term sustainability (Brown and Ulgiati, 2004; Asgharipour et al., 2019). The greater proportion of renewable resources from purchased inputs in the rice production system compared to the cotton cropping system contributed to the higher renewability of the rice system. The amount of renewable energy in this study was greater than 1% for wheat and corn production systems in southwest Iran (Houshyar et al., 2018) and significantly less than 43.2% and 35.4%, respectively, for production of dates and pistachios in the southeast of the country (Jafari et al., 2018).

Table 3. Natural and economic flow, renewability, transformity and solar emergy for cotton

Variable	Unit	Raw annual flow	Renewability factor	Solar transformity (sej unit^{-1})	Solar emergy (sej ha^{-1} yr^{-1})	Solar emergy (%)	References for transformity
				Renewable environmental inputs			
Solar energy	J	3.17E+13	1	1.00E+00	3.17E+13	0.06	definition
Wind, kinetic energy	J	1.43E+10	1	1.25E+03	1.79E+13	0.02	(Campbell and Erban, 2017)
Rain, chemical	J	2.60E+10	1	2.25E+04	5.85E+14	1.04	(Asgharipour et al., 2019)
Rain evapotranspiration	J	2.10E+10	1	2.88E+04	7.58E+14	1.47	(Asgharipour et al., 2019)
Subtotal					7.90E+14	1.53	
				Non-renewable environmental inputs			
Groundwater	J	9.10E+10	0	1.92E+05	1.75E+16	34.04	(Cuadra and Rydberg, 2006)
Groundwater evapotranspiration	J	6.88E+10	0	2.88E+04	1.98E+15	3.05	(Asgharipour et al., 2019)
SoilOrganicMatterreduction	J	9.49E+10	0	9.36E+04	8.88E+15	17.27	(Brandt-Wiliams, 2002)
Soil erosion	J	1.13E+07	0	1.27E+09	1.44E+16	28.01	(Odum, 1996)
Subtotal					4.28E+16	83.27	
				Purchased inputs			
Nitrogen fertilizer	g	4.20E+04	0	3.09E+10	1.30E+15	2.52	(Brandt-Wiliams, 2002)
Phosphorus fertilizer	g	0.00E+00	0	2.82E+10	0.00E+00	0.00	(Brandt-Wiliams, 2002)
Potash fertilizer	g	0.00E+00	0	2.23E+09	0.00E+00	0.00	(Odum, 1996)
Micro fertilizer	g	2.00E+03	0	3.91E+09	7.82E+12	0.01	(Lan et al., 2002)
Herbicide	g	3.00E+03	0	1.89E+10	5.67E+13	0.10	(Hu et al., 2010)
Insecticide	g	2.00E+03	0	1.89E+10	3.78E+13	0.07	(Hu et al., 2010)
Machinery	g	1.66E+04	0	1.01E+10	1.68E+14	0.32	(Campbell et al., 2005)
Fossil fuel and lubricant	J	9.31E+09	0	8.60E+04	8.01E+14	1.55	(Odum, 1996)
Electricity	J	1.19E+09	0.02	2.31E+05	2.75E+14	0.53	(Asgharipour et al., 2019)
Human labor	J	1.36E+09	0.10	2.22E+06	3.02E+15	5.87	(Lu et al, 2009)
Installation of irrigation	Rials	2.07E+06	0	2.50E+08	6.76E+14	1.31	(Amiri et al., 2020)
Seed	Rials	2.10E+07	0.37	6.76E+07	1.42E+15	2.76	(Lan et al., 2002)
Transplant	Rials	0.00E+00	0.43	1.00E+00	0.00E+00	0.00	definition
Subtotal					7.76E+15	15.20	
Total					5.14E+16	100.00	
Economic yield	g	4.50E+06		1.14E+10	5.14E+16		Calculated
Economic yield	J	5.31E+10		9.68E+05	5.14E+16		Calculated

Table 4. The values of emergy indices in rice and cotton production systems

Index	Unit	Rice ecosystem	Cotton ecosystem
Transformity	sej j^{-1}	9.81E+05	9.68E+05
Specific emergy	sej g^{-1}	1.50E+10	1.14E+10
Renewability	%	3.67	3.17
Emergy yield ratio	-	5.13	6.62
Standard emergy investment ratio	-	0.24	0.18
Modified emergy investment ratio		24.11	9.82
Emergy self-support ratio	-	0.81	0.85
Standard environmental loading ratio	-	123.13	64
Modified environmental loading ratio	-	26.33	30.55
Standard emergy sustainability index	-	0.04	0.10
Modified emergy sustainability index	-	0.19	0.22
Emergy exchange ratio	-	0.40	1.10
Emergy index for sustainable development	-	0.02	0.11

3.2.3. Emergy yield ratio (EYR)

The value of EYR in this research for rice and cotton farming ecosystems was 5.13 and 6.62, respectively (Table 4), showing that the cotton farming ecosystem in Golestan province has higher resource consumption efficiency than the rice farming ecosystem. The lowest value for EYR is one, indicating that the contribution of environmental resources to a production system is at its lowest level and reliance on economic resources is at its highest; Therefore, higher values for this index are preferable (Asgharipour et al., 2019). Implementation of strategies to reduce the consumption of economic resources, such as modernizing machines and irrigation pumps to increase efficiency and as a result reduce fuel consumption (as an economic input) can increases this index and, consequently, the consumption efficiency of agricultural systems. This index is the result of dividing the total emergy output (environmental and purchased) by the purchased emergy input. Therefore, decreasing the consumption of economic resources and increasing the consumption of environmental inputs is an effective strategy for increasing this index and enhancing efficiency (Odum, 2000).

3.2.4. Standard emergy investment ratio (EIR) and Modified emergy investment ratio (EIR*)

The value of EIR in this research for rice and cotton cropping systems was 0.24 and 0.18, respectively (Table 4), which indicates the higher efficiency of the cotton cropping system compared to rice. Lower values for this index in a system indicate lower economic costs and greater dependence on the environment and are more desirable (Odum, 2000). Therefore, increasing the proportion of environmental resources in the production system and decreasing the consumption of economic inputs such as replacing these inputs with environmental resources (e.g., using environmental energy sources for electricity and fuel or biological control of pests), can effectively reduce this index and enhance economic efficiency and sustainability. The value of EIR in this study for rice and cotton production systems in Golestan province was significantly lower than the values of 2.29 for the potato production system in this province, Iran (Shahhoseini et al., 2022a) which shows the higher efficiency of the studied systems in this research compared to the mentioned agricultural systems.

The modified emergy investment ratio, EIR* which is the ratio of market resources to free environmental renewable inputs, provides a more direct measure of the compatibility of market inputs with free renewable environmental resources and as a result, demonstrates the competitive advantages provided by the system more effectively (Amiri et al., 2019). This index was used to assess the adaptation of foreign investment in rice and cotton production systems relative to free renewable environmental resources. Its values were 24.11 and 9.82 for rice and cotton production systems, respectively. The higher EIR and EIR* in the rice production system compared to cotton, indicate higher production costs in the rice farming system and greater economic efficiency in the cotton farming ecosystem in the study area. The value of EIR* for rice and cotton production in this study is significantly lower than the values of 21.87, 25.30, 40.93 and 3.70, respectively for mechanized production, traditional, protection and natural habitat of garlic production in Lorestan province, Iran (Amiri et al., 2021).

3.2.5. Emergy self-support ratio (ESR)

In this study, the ESR value for rice and cotton farming ecosystems was 0.81 and 0.85, respectively (Table 4), indicating that these systems are highly reliant on the environment and have a substantial capacity to increase profitability and economic investment. The greater the value of this index, the more sustainable a production system is (Xi and Qin, 2009). Based on this, the cotton production system in the studied region is more sustainable than the rice system. Increasing the proportion of renewable environmental inputs in agricultural systems, such as the use of sunlight (as an environmental source) to generate electricity for irrigation pumps, will increase this index and make agricultural systems more sustainable. In this study, the value of ESR for rice and cotton production systems was significantly higher than the value of 0.03 calculated for the potato production system in China (Zhai et al., 2017), indicating that rice and cotton production systems in the study area are more sustainable than the mentioned system.

3.2.6. Standard environmental loading ratio (ELR) and modified environmental loading ratio (ELR*)

This index for rice and cotton farming ecosystems was 123.13 and 64.00, respectively (Table 4), indicating the significant environmental impact of these two production systems. The main cause of this problem is the excessive use of groundwater and soil erosion (as non-renewable environmental inputs) in rice and cotton farming ecosystems, as well as the excessive use of economic inputs, particularly nitrogen fertilizer, which has led to the concentration of a large flow of non-renewable resources in a small environment. Lower values of this index are preferable (Lu et al., 2014). The ELR is determined by dividing the sum of economic and nonrenewable environmental inputs by renewable environmental inputs. Changing the quantity and quality of consumption of these inputs to reduce their proportion of total emergy input is therefore effective in reducing environmental pressure. According to information gathered from questionnaires, traditional irrigation methods were used in the majority of the studied fields (flooding). This issue was especially evident in the rice fields, where water is constantly placed at the base of the plants during the growing season. Traditional irrigation techniques have not only led to an increase in groundwater consumption, but also in the loss of soil organic matter and soil erosion. The use of new irrigation techniques (such as rain irrigation) and the use of new cultivars with a shorter growing period are effective in reducing water consumption, organic matter loss, and soil erosion. Therefore, measures should be taken to educate and train farmers as well as provide them with financial assistance for the preparation or renovation of irrigation systems. Additionally, increasing the area of cultivation to reduce the concentration of non-renewable inputs, implementing conservation tillage methods to reduce soil erosion (as a non-renewable environmental input), and using renewable resources to provide economic inputs, such as using organic fertilizers instead of chemicals, are effective in reducing environmental pressure and thereby enhancing the sustainability of rice and cotton production systems. Although the value of ELR was high in both the rice and cotton production systems, the value of this index in the cotton system was roughly half that of the rice system (Table 4), indicating that cotton production is significantly more environmentally sustainable than rice production in the study area.

Table 4 reveals that the ELR* values for rice and cotton farming ecosystems are 26.33 and 30.55, respectively, indicating a high level of environmental stress in these two production systems. The values <2, 2-10, and >10 in the ELR and ELR* indices indicate low, medium, and high environmental pressure, respectively (Brown and Ulgiati, 2004). The difference between ELR* and ELR is the transfer of renewable purchased inputs from the ELR denominator to the ELR* denominator. Due to the negligible proportion of renewable purchased resources in rice and cotton farming system´s total emergy input, the amount of ELR* and ELR was high in both production systems. Therefore, the recommended solutions to reduce the amount of ELR, particularly the reduction of non-renewable environmental inputs, are also effective in reducing the amount of ELR*.

In addition to the conversion factor, this index emphasizes the lack of correlation between renewable and nonrenewable resources (Martin et al., 2006). Considering that ELR* is the ratio of non-renewable inputs to renewable inputs, decreasing the proportion of non-renewable resources will decrease this index and make the ecosystem more sustainable in the long term. Over time, nonrenewable resources become increasingly scarce. Despite the vastly greater amount of ELR in rice production compared to cotton, the amount of ELR* in the rice cropping system was somewhat lower than that of cotton due to a greater proportion of renewable inputs in the rice cropping system´s total purchased inputs. This study´s ELR* value for rice and cotton farming ecosystems is greater than the values of 4.18, 4.35, 4.46, and 4.62, respectively for greenhouse production of cucumber, tomato, bell pepper, and Eggplant in Jiroft, Iran (Asgharipour et al., 2020), and 0.62, 1.50, and 1.38, respectively for the production of rice, vegetables, and rotation of rice and vegetables in China (Lu et al., 2010).

3.2.7. Standard emergy sustainability index (ESI) and modified emergy sustainability index (ESI*)

This index was 0.04 for rice farming ecosystems and 0.10 for cotton farming ecosystems, respectively (Table 4). The systems for which this index is less than one are extremely energy intensive, exacerbate environmental effects, and necessitate a great deal of energy for survival (Ulgiati and Brown, 1998). Despite the importance of energy efficiency in sustainable agriculture, the most important reason for the low ESI in rice and cotton farming systems, according to questionnaire data, is the high proportion of non-renewable environmental inputs (groundwater and soil erosion) in total emergy input and the excessive consumption of some economic inputs such as nitrogen fertilizer, seedlings (for rice) and seeds (for cotton) in these production systems. Informing, encouraging, and training farmers about the advantages of implementing new methods of irrigation and conservation tillage, modernizing machinery, using quality seeds, using animal fertilizers instead of chemicals (as much as possible), and using renewable energy sources are effective in reducing the consumption of non-renewable environmental and economic inputs and, as a result, reducing environmental pressure and increasing the economic sustainability of agriculture. In production systems, increasing yield and decreasing environmental pressure increases ESI and, consequently, economic sustainability (Jafari et al., 2018). Despite the low levels of ESI in both rice and cotton production systems, the value of this index in the cotton cropping system was more than twice that of the rice cropping system, indicating that cotton production in the study area is significantly more sustainable than rice production.

ESI* is an inverse sustainability scale related to a system´s performance ratio that expresses the system´s advantages in relation to its relative sustainability. Zero and infinity are the minimum and maximum values for this index, respectively (Lu et al., 2014). This index was 0.19 for rice farming ecosystems and 0.22 for cotton farming ecosystems, respectively (Table 4). Higher values of both indices indicate greater ecological sustainability of the system. The values >10, 1-10, and <1 in both the ESI and ESI* indices, respectively, represent a sustainable system with very low pressure, living and good systems, and resource-depleting systems (Asgharipour et al., 2019).

Considering the importance of environmental sustainability in maintaining the economic advantage of a production system, the most advantageous policy for rice and cotton production in the province of Golestan is to maintain the system´s equilibrium between economic advantage and environmental sustainability. Increasing the proportion of renewable resources, including the substitution of renewable resources for nonrenewable resources in the provision of economic inputs, is effective in reducing pressure and enhancing environmental sustainability, thereby enhancing ESI* in rice and cotton farming systems. Similarly to ESI, the value of ESI* in the cotton cropping system was greater than in the rice cropping system, indicating cotton production in the study area is more sustainable than rice production. The ESI* value in this study is less than the values of 0.45, 1.83 and 0.77, respectively for the production of corn (Zhang et al., 2012), rice and rotation of rice and vegetables (Lu et al., 2010) in China.

3.2.8. Emergy exchange ratio (EER)

Emergy exchange ratio is a dual-purpose index used for both emergy and economic assesments (Odum, 1996). EER represents the emergy exchange based on product performance per unit area and analyzes the emergy benefits resulting from product sales. This index measures the equilibrium between the market-exchanged economic output (in sej ha^{-1}) and the total emergy input to the system. Values greater than one for this index indicate a favorable situation for a production system in terms of index and are appealing to farmers (Asgharipour et al., 2020). The value of EER in this research for rice and cotton farming ecosystems was 0.40 and 1.10, respectively (Table 4), which indicates more sustainability of cotton production. Because it shows that the purchasing power of the money received to buy emergy on the market in exchange for a product output from the cotton production system is 1.10 greater than the ratio of input emergy used to produce output in this system. This index is higher in the cotton farming system due to the lower emergy input per unit of economic output exchanged for money on this product´s market. Accurate management of crop production, such as the correct implementation of tillage operations, proper and sufficient irrigation, and fighting against pests and weeds at the optimal time, as well as proper planting, is effective for increasing yield and decreasing the proportion of emergy input per unit of economic output, thereby increasing the EER value in the rice production system. China´s guava, papaya, and banana production systems have reported EER values 1.9, 3.6, and 1.8, respectively (Lu et al., 2009).

3.2.9. Emergy index for sustainable development (EISD)

This index evaluates the effects of market feedback on the environmental sustainability of the system and the effects of market exchange on the emergy efficiency of the system. EISD combines the EER and ESI results. The greater value of this index indicates the system´s sustainability from the perspective of the effects of economic interdepence (Asgharipour et al., 2020). In this study, the EISD values for rice and cotton farming ecosystems were 0.02 and 0.11, respectively, indicating that cotton farming system is significantly more sustainable than the rice production system. In addition to increasing yield, the implementation of appropriate management solutions with the goal of reducing environmental pressure, such as reducing the consumption of non-renewable resources and using renewable resources instead (as much as possible), will be effective in increasing this index and thereby improving the sustainability of rice production. The reported EISD values for the production of guava, papaya, and bananas in China are 0.71, 0.55, and 0.24, respectively (Lu et al., 2009).

4. Conclusion

This study evaluated and compared the efficiency and sustainability of rice and cotton farming ecosystems using emergy indices. This study revealed that the density of emergy in the rice farming ecosystem was significantly higher than that of cotton. In both rice and cotton farming ecosystems, non-renewable environmental inputs comprised a much larger proportion of total emergy input than renewable environmental inputs, renewable purchased inputs, and non-renewable purchased inputs. In the meantime, the proportion of groundwater from all 21 inputs evaluated in this study was greater in both investigated ecosystems due to the high water demand of these two crops and their summer cultivation, as well as high evapotranspiration and negligible precipitation during this season in the study area.

The evaluation of Tr and SpE indicators revealed that the cotton farming ecosystem is more productive than the farming ecosystem. The low index of %R in both production systems was a result of their heavy reliance on nonrenewable environmental resources. However, the renewability of the rice production system was greater than that of cotton, and the primary reason for this was the greater proportion of renewable resources in the rice cropping system´s purchased inputs compared to cotton. Based on the EYR, the cotton cropping system utilized resources more efficiently than rice. The analysis of standard and modified EIR revealed that the economic costs and economic efficiency of the rice production system are significantly higher than those of cotton. The evaluation of the ESR revealed that, compared to rice, the cotton farming system is more environmentally dependent and has a high potential for increasing investment and economic productivity. According to the analysis of ELR, both systems place a substantial burden on the environment. This was due to the excessive use of non-renewable inputs, such as groundwater, which led to an increase in soil organic matter loss and soil erosion, as well as the excessive and unprincipled use of nitrogen fertilizer in both systems. However, the ELR in the cotton farming system was roughly half that of the rice production system, indicating that this system is significantly more environmentally sustainable than rice farming. The implementation of new irrigation and conservation tillage techniques, as well as the use of organic fertilizers such as animal manure, are effective in reducing the consumption of nonrenewable resources, thereby reducing environmental pressure and enhancing environmental sustainability in these two systems.

The evaluation of Emergy's sustainability indicators revealed that the rice farming ecosystem´s economic sustainability is roughly half that of the cotton production system. This is due to the rice farming ecosystem´s high dependence on certain economic inputs and high environmental pressure. Along with maintaining or enhancing performance in this agricultural system, reducing the consumption of purchased resources, particularly purchased nonrenewable resources will improve these indices and increase economic sustainability. Reduce the consumption of fossil fuels as much as possible through the renovation of irrigation equipment and pumps and the use of renewable energy, such as sunlight, to generate electricity. On the basis of the evaluation of the EER, the purchasing power of the money received to purchase emergy on the market in exchange for a product output from the cotton production system is significantly greater than the ratio of input emergy used to produce the output in this system compared to the rice production system. This index is higher in the cotton farming system due to the lower emergy input per unit of economic output exchanged for money on this product´s market.

Accurate management of crop production, such as the correct implementation of tillage operations, proper and sufficient irrigation, and combating pests and weeds at the most appropriate time and appropriate planting, is effective at increasing yield and decreasing the proportion of emergy input per unit of economic output, thereby increasing the value of this index in the rice production system. The value of the emergy index for sustainable development in the cotton production system was significantly higher than that of the rice production system, indicating that the cotton agricultural system is significantly more sustainable than the rice production system. In addition to increasing yield, the implementation of appropriate management solutions with the goal of reducing environmental pressure, such as reducing the consumption of non-renewable resources and using renewable resources instead (as much as possible), will be effective in increasing this index and thereby improving the sustainability of rice production.

In the cotton farming ecosystem, production efficiency, resource consumption efficiency, economic efficiency, environmental sustainability, and economic sustainability were all higher than in the rice farming ecosystem. Effective are the implementation of the recommended solutions to reduce the consumption of nonrenewable resources and the use of renewable resources in providing purchased inputs, as well as awareness, education, and encouragement of farmers in these fields, in enhancing the environmental and economic sustainability of agricultural ecosystems.

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Appendix A

1) Rice farm

1- Solar energy (J ha^{-1}): (area, 1 ha) × (10,000 m^2 ha^{-1}) × (during growth season, 3.74E+09 J m^{-2}) × (1-albedo, 0.8) = 2.99E+13 J ha^{-1} (Asgharipour et al., 2020).

2- Wind, kinetic energy (J ha^{-1}): (area, 1 ha) × (10,000 m^2 ha^{-1}) × (air density, 1.3 kg m^{-3}) × (drag coefficient, 0.002) × (wind velocity × 3.7 m s^{-1})^3 × (growth season, 7.97E+6 s) = 1.05E+10 J ha^{-1} (Asgharipour et al., 2020).

3- Rain, chemical potential energy (J ha^{-1}): (area, 1 ha) × (10,000 m^2 ha^{-1}) × (rainfall, 0.548 m yr^{-1}) (density, 1,000 kg m^{-3}) (Gibbs free energy, 4,740 J kg^{-1}) = 2.60E+10 J ha^{-1} (Asgharipour et al., 2020).

4- Rain evapotranspiration energy (J ha^{-1}): (area, 1 ha) × (10,000 m^2 ha^{-1}) × (transpiration, 0.459 m yr^{-1}) × (density, 1,000 kg m^{-3}) × (Gibbs free energy, 4,740 J kg^{-1}) = 2.18E+10 J ha^{-1} (Asgharipour et al., 2020).

5- Ground water energy (J ha^{-1}): (area, 1 ha) × (10,000 m^2 ha^{-1}) × (average quantity, 4.82 m^3 m^{-2}) × (conversion, 1000 kg m^{-3}) × (Gibbs free energy, 4,690 J kg^{-1}) = 2.26E+11 J ha^{-1} (Asgharipour et al., 2020).

6- Ground water evapotranspiration energy (J ha^{-1}): (area, 1 ha) × (10,000 m^2 ha^{-1}) × (transpiration, 1.80 m yr^{-1}) × (density, 1,000 kg m^{-3}) × (Gibbs free energy, 4,740 J kg^{-1}) = 8.53E+10 J ha^{-1} (Asgharipour et al., 2020).

7- SOM change: -0.10%

SOM reduction weight = (area, 1 ha) × (10,000 m^2 ha^{-1}) × (0.3 m, soil layer) × (1400 kg m^{-3}, Soil bulk density) × (-0.10%) = -4,200 kg ha^{-1}

SOM reduction energy: (4,200 kg ha^{-1}, SOM reduction weight) × (5400 kcal kg^{-1}) × (4186 J kcal^{-1}) = 9.49E+10 J ha^{-1} (Asgharipour et al., 2020).

8- Soil erosion (J ha^{-1}):

Average soil loss from water erosion calculated by USLE model to be 20.59tones ha^{-1}

Soil erosion = (area, 1 ha) × (soil loss rate, 20.59 tones ha^{-1}) × (1.0E+06 g tones^{-1}) = 2.06E+07 g ha^{-1} (Asgharipour et al., 2020).

9- Human labor (J ha^{-1}): (Working hour, 602 h ha^{-1}) × (1.96E+06 J h^{-1}) = 1.18E+09 J ha^{-1} (Asgharipour et al., 2020).

10- Agricultural Machinery steel (gr ha^{-1}):

1. Tractor: (Steel weight, 3.60E+06 g × work hours, 19 h ha^{-1}) = 6.84E07 g h ha^{-1}
2. Carrier tractor trail: (Steel weight, 7.50E+05 g × work hours, 2 h ha^{-1}) = 1.50E06 g h ha^{-1}
3. Moldboard plow: (Steel weight, 7.00E+05 g × work hours, 3 h ha^{-1}) = 2.10E06 g h ha^{-1}
4. Disc plow: (Steel weight, 6.00E+05 g × work hours, 1 h ha^{-1}) = 6.00E05 g h ha^{-1}
5. Leveler: (Steel weight, 4.00E+05 g × work hours, 3 h ha^{-1}) = 1.20E06 g h ha^{-1}
6. Planter: (Steel weight, 1.00E+06 g × work hours, 1 h ha^{-1}) = 1.00E06 g h ha^{-1}
7. Harrows: (Steel weight, 6.00E+05 g × work hours, 5 h ha^{-1}) = 3.00E06 g h ha^{-1}
8. Combine harvester: (Steel weight, 4.70E+06 g × work hours, 2 h ha^{-1}) = 9.40E06 g h ha^{-1}
9. Truck: (Steel weight, 9.00E+06 g × work hours, 2 h ha^{-1}) = 1.80E07 g h ha^{-1}

Assume an economic life of 15 years, yearly work hours 540 h).

Agricultural Machinery (g ha^{-1}) = Σ (steel × work hours /economic life/yearly work hours) = 1.34E+04 gr ha^{-1} (Asgharipour et al., 2020).

11- Fuel for machinery (J ha^{-1}): (average quantity, 254kg ha^{-1}) × (conversion, 4.67E+07 J kg^{-1}) = 1.19E+10 J ha^{-1} (Asgharipour et al., 2020).

12- Electricity (J ha^{-1}): (average quantity, 1000 kWh ha-1) × (conversion, 3.6E+06 J kWh^{-1}) = 3.60E+09 J ha^{-1} (Asgharipour et al., 2020).

2) Cotton farm

1- Solar energy (J ha^{-1}): (area, 1 ha) × (10,000 m^2 ha^{-1}) × (during growth season, 3.93E+09 J m^{-2}) × (1-albedo, 0.8) = 3.17E+13 J ha^{-1} (Asgharipour et al., 2020).

2- Wind, kinetic energy (J ha^{-1}): (area, 1 ha) × (10,000 m^2 ha^{-1}) × (air density, 1.3 kg m^{-3}) × (drag coefficient, 0.002) × (wind velocity × 3.7 m s^{-1})^3 × (growth season, 1.090E+7 s) = 1.43E+10 J ha^{-1} (Asgharipour et al., 2020).

3- Rain, chemical potential energy (J ha^{-1}): (area, 1 ha) × (10,000 m^2 ha^{-1}) × (rainfall, 0.548 m yr^{-1}) (density, 1,000 kg m^{-3}) (Gibbs free energy, 4,740 J kg^{-1}) = 2.60E+10 J ha^{-1} (Asgharipour et al., 2020).

4- Rain evapotranspiration energy (J ha^{-1}): (area, 1 ha) × (10,000 m^{2} ha^{-1}) × (transpiration, 0.442 m yr^{-1}) × (density, 1,000 kg m^{-3}) × (Gibbs free energy, 4,740 J kg^{-1}) = 2.10E+10 J ha^{-1} (Asgharipour et al., 2020).

5- Ground water energy (J ha^{-1}): (area, 1 ha) × (10,000 m^{2} ha^{-1}) × (average quantity, 1.94 m^{3} m^{-2}) × (conversion, 1000 kg m^{-3}) × (Gibbs free energy, 4,690 J kg^{-1}) = 9.10E+10 J ha^{-1} (Asgharipour et al., 2020).

6- Ground water evapotranspiration energy (J ha^{-1}): (area, 1 ha) × (10,000 m^{2} ha^{-1}) × (transpiration, 1.451 m yr^{-1}) × (density, 1,000 kg m^{-3}) × (Gibbs free energy, 4,740 J kg^{-1}) = 6.88E+10 J ha^{-1} (Asgharipour et al., 2020).

7- SOM change: -0.10%

SOM reduction weight = (area, 1 ha) × (10,000 m^{2} ha^{-1}) × (0.3 m, soil layer) × (1400 kg m^{-3}, Soil bulk density) × (-0.10%) = -4,200 kg ha^{-1}

SOM reduction energy: (4,200 kg ha^{-1}, SOM reduction weight) × (5400 kcal kg^{-1}) × (4186 J kcal^{-1}) = 9.49E+10 J ha^{-1} (Asgharipour et al., 2020).

8- Soil erosion (J ha^{-1}):

Average soil loss from water erosion calculated by USLE model to be 11.30 tones ha^{-1}

Soil erosion = (area, 1 ha) × (soil loss rate, 11.30 tones ha^{-1}) × (1.0E+06 g tones^{-1}) = 1.13E+07 g ha^{-1} (Asgharipour et al., 2020).

9- Human labor (J ha^{-1}): (Working hour, 693 h ha^{-1}) × (1.96E+06 J h^{-1}) = 1.36E+09 J ha^{-1} (Asgharipour et al., 2020).

10- Agricultural Machinery steel (gr ha^{-1}):

1. Tractor: (Steel weight, 3.60E+06 g × work hours, 21 h ha^{-1}) = 7.56E07 g h ha^{-1}
2. Carrier tractor trail: (Steel weight, 7.50E+05 g × work hours, 2 h ha^{-1}) = 1.50E06 g h ha^{-1}
3. Moldboard plow: (Steel weight, 7.00E+05 g × work hours, 5 h ha^{-1}) = 3.50E06 g h ha^{-1}
4. Disc plow: (Steel weight, 6.00E+05 g × work hours, 1 h ha^{-1}) = 6.00E05 g h ha^{-1}
5. Leveler: (Steel weight, 4.00E+05 g × work hours, 3 h ha^{-1}) = 1.20E06 g h ha^{-1}
6. Planter: (Steel weight, 1.00E+06 g × work hours, 1 h ha^{-1}) = 1.00E06 g h ha^{-1}
7. Harrows: (Steel weight, 6.00E+05 g × work hours, 9 h ha^{-1}) = 5.40E06 g h ha^{-1}
8. Truck: (Steel weight, 9.00E+06 g × work hours, 5 h ha^{-1}) = 4.50E07 g h ha^{-1}

Assume an economic life of 10 years, yearly work hours 540 h).

Agricultural Machinery (g ha^{-1}) = Σ (steel × work hours /economic life/yearly work hours) = 1.66E+04 gr ha^{-1} (Asgharipour et al., 2020).

11- Fuel for machinery (J ha^{-1}): (average quantity, 199.3kg ha^{-1}) × (conversion, 4.67E+07 J kg-1) = 9.31E+09 J ha^{-1} (Asgharipour et al., 2020).

12- Electricity (J ha^{-1}): (average quantity, 330 kWh ha-1) × (conversion, 3.6E+06 J kWh^{-1}) = 1.19E+09 J ha^{-1} (Asgharipour et al., 2020).